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Aircraft Structures Technical Memorandum 513

A SUMMARY OF THE BODNER-STOUFFER CONSTITUTIVE MODEL (U)

by

N. BRIDGFORD

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SUMMARY

A set of constitutive equations has recently been developed to model non-linear material behaviour of high temperature superalloys. This paper summarises the governing equations of this new model and presents a simple FORTRAN program which implements these equations for the one-dimensional case.

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1. INTRODUCTION

Classical techniques of modelling creep and plasticity have a high degree of accuracy provided the inelastic strains are kept small. However, they are poor in describing material behaviour where significant inelastic strains or unloading are involved.

In a recent investigation [1], a number of "unified" constitutive models were examined. In these approaches, a single inelastic strain tensor is used to model both creep and plasticity. A new constitutive equation was then proposed.

This report describes this new approach, and discusses a FORTRAN program * which uses these new equations to predict material behaviour. Given either stress or strain values as input data, it evaluates the "state variables", i.e. drag stress, back stress etc., the inelastic strain rate and the inelastic work.

2. NEW UNIFIED CONSTITUTIVE MODEL

2.1 Theory

The unified constitutive model developed by Ramaswarmy [illegible] based on the generic back stress and drag stress model proposed by Bodner [2] and Stouffer [3]. The Bodner-Stouffer flow law can be written as

$$\dot{\varepsilon}^I_{ij} = \lambda S_{ij} \tag{1}$$

where λ is a scalar material function which can be found using a procedure suggested by Bodner and Stouffer[3]. Including a back stress in the model

* Developed by Prof. D.C. Stouffer and V.S. Battachar at the University of Cincinatti, Ohio, U.S.A.

allows the inelastic strain rate vector $\dot{\epsilon}^I_{ij}$ and the deviatoric stress vector S_{ij} to have different directions, and results in a flow rule of the form

$$\dot{\epsilon}^I_{ij} = \lambda \left(S_{ij} - \Omega_{ij} \right). \tag{2}$$

Squaring (2) and defining

$$D^I_2 = \frac{1}{2} \dot{\epsilon}^I_{ij} \dot{\epsilon}^I_{ij} \tag{3}$$

and

$$K_2 = \frac{1}{2} \left(S_{ij} - \Omega_{ij} \right) \left(S_{ij} - \Omega_{ij} \right) \tag{4}$$

as the second invariants of the inelastic strain rate tensor and the effective deviatoric stress tensor respectively, then the flow equation can be rewritten as

$$\dot{\epsilon}^I_{ij} = \sqrt{D^I_2} \frac{\left(S_{ij} - \Omega_{ij} \right)}{\sqrt{K_2}}. \tag{5}$$

It is normal to assume the form of $\sqrt{D^I_2}$ as

$$\sqrt{D^I_2} = D \exp \left[-\frac{A}{2} \left(\frac{Z^2}{3K_2} \right)^n \right] \tag{6}$$

where D, A and n are temperature dependent material parameters. In this case the general flow equation can be written as

$$\dot{\epsilon}^I_{ij} = D \exp \left[-\frac{A}{2} \left(\frac{Z^2}{3K_2} \right)^n \right] \frac{\left(S_{ij} - \Omega_{ij} \right)}{\sqrt{K_2}}. \tag{7}$$

This is the form of the flow equation used in the FORTRAN program.

The back stress Ω and the drag stress Z used in these equations are "state variables" which cannot be measured directly. They are represented in the form of evolution equations, where their rate of change with respect to time depends upon the current state of stress, inelastic strain rate, temperature and internal variables, viz:

$$\dot{\Omega} = F_1\left(\sigma_{ij}, \dot{\epsilon}^I_{ij}, \Omega_{ij}, Z, T\right) \tag{8}$$

and

$$\dot{Z} = F_2\left(\sigma_{ij}, \dot{\epsilon}^I_{ij}, \Omega_{ij}, Z, T\right). \tag{9}$$

The multiaxial form of the back stress evolution equation used in the FORTRAN program is

$$\dot{\Omega}^I_{ij} = f_1 \dot{\epsilon}^I_{ij} - \frac{3}{2} f_1 \frac{\Omega_{ij}}{\Omega_{max}} \dot{\epsilon}^I_{eff} \tag{10}$$

where f_1, G and Ω_{max} are scalar parameters determined from uniaxial experiments, and where, for a uniaxial loading condition, the effective inelastic strain rate is defined as

$$\dot{\epsilon}^I_{eff} = \sqrt{\frac{2}{3} \dot{\epsilon}^I_{ij} \dot{\epsilon}^I_{ij}}. \tag{11}$$

Also,

$$\Omega_{ij} = \frac{G}{E} S_{ij} + \Omega^I_{ij} \tag{12}$$

The drag stress Z is a scalar quantity, and is represented by the evolution equation

$$\dot{Z} = m(Z_1 - Z_0)\dot{W}^I + R_2. \tag{13}$$

If temperature effects are insignificant then eqn (13) can be integrated to give

$$Z = Z_1 + (Z_0 - Z_1)\, e^{-mW^I} \tag{14}$$

where Z_0 is the initial value of Z, Z_1 is the saturated value of drag stress, m determines the rate of cyclic softening, and W^I is the inelastic work. Further details of the above equations and their derivations are given in reference [1], whilst reviews of current methods for predicting material behaviour are given in references [1,4].

2.2 Program Summary

A simple FORTRAN program, which we will refer to as MODEL2, has been written to implement this system of constitutive equations, though at present it is only applicable to the one-dimensional case. It may be run in either Stress or Strain control, with either isothermal or non-isothermal conditions. The loading may be either tensile, torsional or a combination of tension or torsion. Input data consists of control variables, load history points (stress or strain), and material data. A complete listing of the input required can be found in the Appendix.

The subroutines called in this program, and a brief description of their functions, are given in Figure 1. A flow chart for the program is presented in Figure 2.

2.3 Detailed Description

- Subroutines INPUT1, INPUT2 and LOADHIST read in and initialise material constants, control parameters and initial values of stress or strain.

• Subroutine TSTEP then determines the time step Δt for the inelastic constitutive equation, using current stress or strain values, the current time step and control parameters.

The new time step Δt^* is taken as the minimum of

(i) $(\Delta t * \Delta t_{init}) / 1E - 10$

(ii) $(\Delta t * \Delta \sigma_{max}) / |\sigma_{max}(t^*) - \sigma_{max}(t)|$

(iii) $(\Delta t * \Delta \varepsilon_{max}) / |\varepsilon_{max}(t^*) - \varepsilon_{max}(t)|$

(iv) $\Delta t_{max} * \Delta t$,

where Δt is current time step, Δt_{max} and Δt_{min} are the maximum and minimum time step factors respectively, Δt_{init} is the initial time step and $t^* = t + \Delta t$.

However, if $\Delta t^* < \Delta t_{min} * \Delta t$ then $\Delta t^* = \Delta t_{min} * \Delta t$.

• Subroutine INTTIME linearly interpolates the stress/strain and temperatures with respect to time. Using subroutine INTTEMP, material constants are also interpolated with respect to time for the non-isothermal case. Subroutine DCCALCS then interpolates the material stiffness matrix $[D]$ and the material compliance matrix $[C]$.

• If the program is running under strain control, inelastic strain is estimated using the equation

$$\varepsilon_{ij}^I(t^*) = \varepsilon_{ij}^I(t) + \Delta t \dot{\varepsilon}_{ij}^I(t). \tag{15}$$

• Subroutine STREPS, running under strain control, calculates elastic strains and evaluates the stresses and total strains as follows

$$\varepsilon_e(t^*) = \varepsilon_{ij}(t^*) - \varepsilon^I_{ij}(t^*)$$

$$\sigma_{ij}(t^*) = [D]\varepsilon_e(t^*) \tag{16}$$

$$\varepsilon_{ij}(t^*) = \varepsilon_e(t^*) + \varepsilon^I_{ij}(t^*).$$

If the program is running under stress control, STREPS calculates only the elastic strains, viz:

$$\varepsilon_e(t^*) = [C]\sigma_{ij}(t^*). \tag{17}$$

and the deviatoric stresses $S_{ij}(t^*)$ are calculated in subroutine DEVSTR.

• The state variables back stress, drag stress and K_2 are evaluated next, along with the total inelastic strain and the inelastic work. These calculations are performed using subroutines DRAG, EFFRAT, BACK, K2CALC, TOTISTR and WORK.

Subroutine DRAG evaluates the drag stress using eqn(14), viz:

$$Z\,(t^*) = Z_1 + (Z_0 - Z_1)\,e^{-mW^I}.$$

Subroutine EFFRAT evaluates the effective inelastic strain rate using eqn(11), viz:

$$\dot{\varepsilon}^I_{eff} = \sqrt{\frac{2}{3}\dot{\varepsilon}^I_{ij}(t^*)\dot{\varepsilon}^I_{ij}(t^*)}.$$

Subroutine BACK evaluates the inelastic back stress rate using eqn(10), and from this finds the total back stress using eqn(12), viz:

$$\Omega_{ij}(t^*) = \Omega^I_{ij}(t^*) + \frac{G}{E} S_{ij}(t^*), \tag{12}$$

where

$$\Omega^I_{ij}(t^*) = \Omega^I_{ij}(t) + \frac{\Delta t}{2}\left(\dot{\Omega}^I_{ij}(t) + \dot{\Omega}^I_{ij}(t^*)\right) \tag{18}$$

and

$$\dot{\Omega}^I_{ij} = f_1 \dot{\varepsilon}^I_{ij} - \frac{3}{2} f_1 \frac{\Omega_{ij}}{\Omega_{max}} \dot{\varepsilon}^I_{eff}. \tag{10}$$

Subroutine K2CALC evaluates K_2, the second invariant of the effective deviatoric stress, from eqn(4), viz:

$$K_2 = \frac{1}{2}(S_{ij}(t^*) - \Omega_{ij}(t^*))(S_{ij}(t^*) - \Omega_{ij}(t^*)).$$

Subroutine FLOW evaluates the inelastic strain rate using eqn(7), viz:

$$\varepsilon^I_{ij}(t^*) = D \exp\left[-\frac{A}{2}\left(\frac{Z^2}{3K_2}\right)^n\right] \frac{(S_{ij}(t^*) - \Omega_{ij}(t^*))}{\sqrt{K_2}}.$$

The total inelastic strain is found in subroutine TOTISTR

$$\varepsilon^I_{ij}(t^*) = \varepsilon^I_{ij}(t) + \frac{\Delta t}{2}\left(\dot{\varepsilon}^I_{ij}(t) + \dot{\varepsilon}^I_{ij}(t^*)\right)$$

and the inelastic work is then evaluated in subroutine WORK

$$W^I(t^*) = W^I(t) + \left(S_{ij}(t^*) + S_{ij}(t)\right)\left(\varepsilon^I_{ij}(t^*) - \varepsilon^I_{ij}(t)\right).$$

- Subroutine CONCHK checks the convergence of inelastic strain and stress.

Convergence is taken to be achieved if either

$$\varepsilon_{ij}^{I}(t^*) = 0$$

or

$$\sigma_{ij}(t^*) = 0$$

or if the calculated percentage error is less than the allowable percentage error for either stress or strain.

If convergence is not achieved the values are reset in subroutine RESET1, and the iteration loop re-entered as shown in the flow chart, Figure 2.

If convergence is achieved, the total strain is then determined and the appropriate values output in subroutine PRINT. Parameters such as the state variables are output to the file OUTPUT.DAT, and the values of the stresses and strains are output to the plot files PLOT1.DAT and PLOT2.DAT. If the analysis is not yet complete, a new time step Δt is determined and the solution is recalculated.

3. DISCUSSION

The program outlined in this report predicts non-linear material behaviour in the simple one-dimensional case. Predictions using this model have been shown [1,2,3] to be in good agreement with experimental results. The governing equations of the Bodner-Stouffer model summarised in this report are applicable to the three-dimensional case. This program could be extended to handle multiaxial loading conditions, and could also be incorporated into a general purpose finite element code.

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3. Stouffer, D.C. and Bodner, S.R., 'A Relationship Between Theory and Experiment for a State Variable Constitutive Equation', American Society for Testing and Materials STP, 765, 239-250, 1982.

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SUBROUTINES:

INPUT1	- Reads Control Data
INPUT2	- Reads Material Constants
LOADHIST	- From control data this sets up the stress/strain and temperature variation curve wrt time
INTTIME	- Interpolates stress/strain & temperature wrt time
INTTEMP	- Interpolates material constants wrt temperature
DCCALC	- Calculates D and C matrix
TSTEP	- Calculates current - new time step dt
STREPS	- Calculates stresses if strain control and elastic strains if stress control
DEVSTR	- Calculates deviatoric stresses at tdt
DRAG	- Calculates Drag stress Z at tdt
EFFRAT	- Calculates effective inelastic strain rate at tdt
BACK	- Calculates Back stress Omega at tdt
K2CALC	- Calculates value of AK2 at tdt
FLOW	- Calculates inelastic strain rate at tdt
TOTISTR	- Calculates total inelastic strain at tdt
WORK	- Calculates inelastic work at tdt
CONCHK	- Check Convergence of values
RESET1	- Resets values if there is no convergence
RESET2	- Resets values if there is convergence
ERRPRT	- Prints error messages into a file
PRINT	- Prints output into a file

Figure 1: Subroutines called in MODEL2

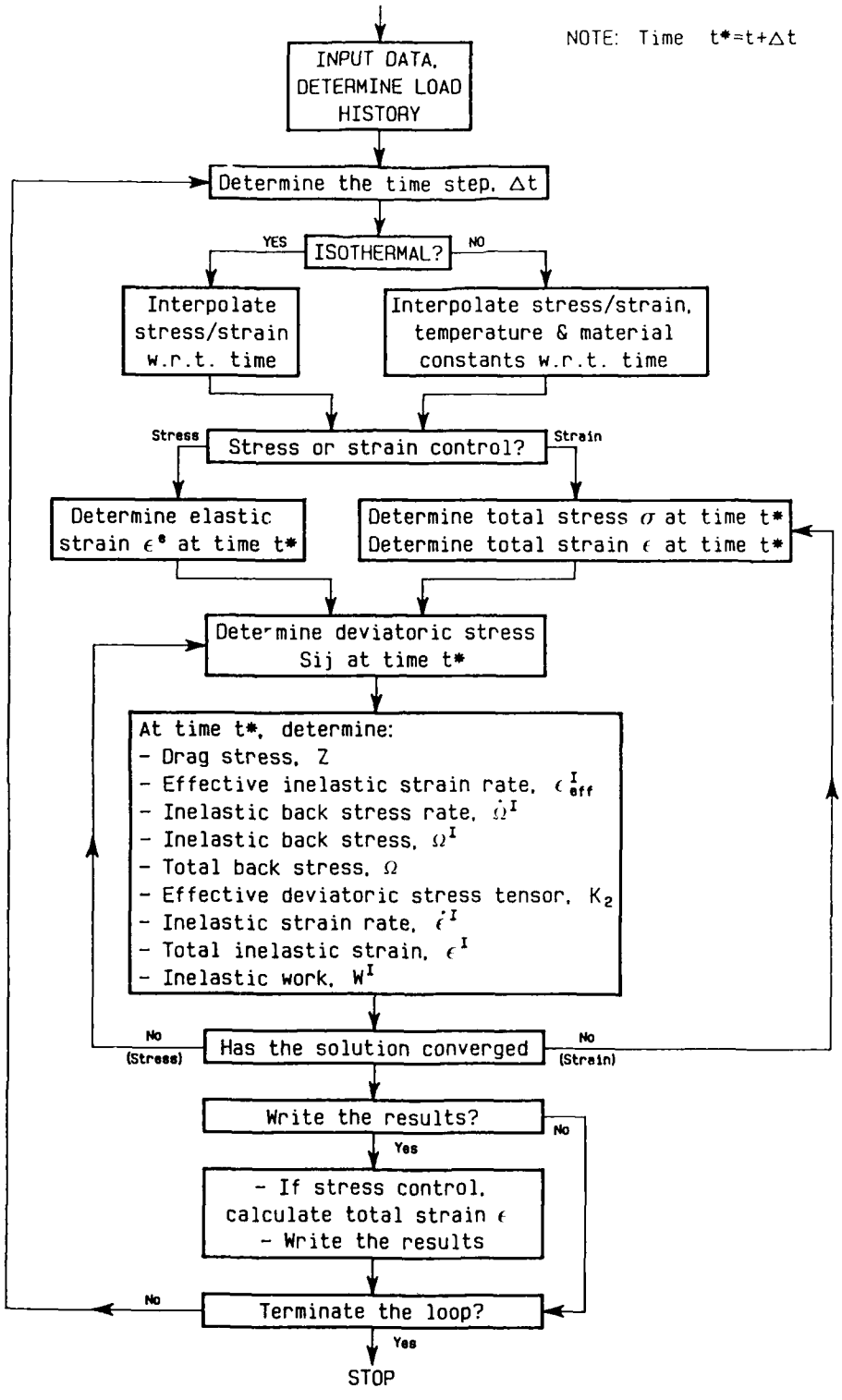

FIGURE 2. FLOW CHART FOR PROGRAM MODEL 2.F

APPENDIX: Variables used in the program MODEL2:

INPUT VARIABLES:

1. TITLES:

*ETITLE - title line in the file INPUT.DAT
**MTITLE - title line in the file MATL.DAT

2. CONTROL VARIABLES:

*NCTL - decides stress/strain control.
= 1 stress control
= 2 strain control
*NTYPE- decides the load type
= 1 tensile load only
= 2 torsional load only
= 3 tension + torsion
*NTHERM- decides isothermal/nonisothermal case
= 1 isothermal
= 2 nonisothermal
*NCYTEN- number of cycles in tension loading = or >1
*NCYTOR- number of cycles in torsion loading = or >1
*NCYTEM- number of cycles in temperature loading
= 1 isothermal
> or = 1 nonisothermal
*NPTEN - number of points in tension loading in
first cycle = or >1
*NPTOR - number of cycles in torsion loading in
first cycle = or >1
*NPTEM - number of cycles in temperature loading in
first cycle = or >1
LASTEN\
LASTOR > last points in respective loadings
LASTEM/

*TSTOP - time at which analysis is stopped = or >0
*ESTOP1- strain in the tension load direction at which
analysis is to be stopped = or >0
*ESTOP2- strain in the shear stress direction at which
analysis is to be stopped = or >0

*DTPR - output printed into OUTPUT.DAT once in DTPR time
steps (time controlled output)
= 0 if not time controlled
> 0 if time controlled
*DEPR1 - output printed once in DEPR1 increase in strain
in the tension direction (strain controlled output)
= 0 if not strain-in-axial-direction controlled
> 0 if strain-in-axial-direction controlled
*DEPR2 - output printed once in DEPR2 increase in strain
in the shear direction (strain controlled output)
= 0 if not strain-in-shear-direction controlled
> 0 if strain-in-shear-direction controlled

```
*CTR(20)-control variables
    (1) -maximum stress step allowable in analysis
    (2) -maximum inelastic strain step
    (3) -maximum inelastic strain rate step
    (4) -maximum time step factor
    (5) -minimum time step factor
    (6) -initial time step

        CTR(1-6) values > 0
```

3. ERROR CONTROL DATA:

```
*PERSTR -allowable % error in stress calculations
*PEREPS -allowable % error in strain calculations
*MAXITER-maximum number of iterations allowable for
         convergence
```

4. MATERIAL CONSTANTS DATA:

```
**NUMCON -number of input material constants(= or <20)
**NUMTEM -number of temperatures at which material
         constants are being input(= or <10)
**CONS(20,10)-material constants.

  CONS(I,J)  I = 1,20   J = 1,10

  I = 1  : A
      2  : D
      3  : YOUNGS MODULUS
      4  : f1
      5  : g
      6  : m
      7  : n
      8  : poissons ratio
      9  : Z0
      10 : Z1
      11 : OMEGA MAX.

 CONINT(20)-interpolated material constants

 D(6,6) -material stiffness matrix
 C(6,6) -material compliance matrix
```

5. INPUT LOAD DATA:(strain inputs are tensor strain values)

```
*DXTTEN(10,2) - tensile load points in the first cycle
                (stress/strain)
*DXTTOR(10,2) - torsion load points in the first cycle
                (stress/strain)
*DXTTEM(10,2) - temperature load points in the first cycle

      DXT...(I,1) PARAMETER VALUE
      DXT...(I,2) TIME VALUE
```

6. TEMPERATURE VARIABLES:

**TEMDAT(10)-temperatures at which material constants have been input

NOTE: 1. ALL STRAIN INPUTS are TENSOR values except the values of the strains which are printed into PLOT1 and PLOT2.DAT files; these are engineering strain values.

2. A `*' before the variable indicates it is an input from the file `INPUT.DAT'.

3. A `**' before the variable indicates it is an input from the file `MATL.DAT'.

INTERNAL AND OUTPUT VARIABLES:

7. CALCULATED LOAD DATA:

DATTEN(500,2) - data points in the entire load history
DATTOR(500,2) - in the respective cycles.
DATTEM(500,2) -

DAT...(I,1) PARAMETER VALUE
DAT...(I,2) TIME VALUE

8. STRESS VARIABLES:

STR_t(6) -stress at time t
STR_tdt(6)-stress at time t+dt
PSTR(6) -stress at t+dt stored from the last iteration
DEVS_t(6) -deviatoric stress at time t
DEVS_tdt(6) -deviatoric stress at time t+dt

9. STRAIN VARIABLES:(all strains are tensor strains !)

EPS_t(6) -total strain at time t
EPS_tdt(6)-total strain at time t+dt

EPSE_t(6)-elastic strain at time t
EPS_tdt(6)-elastic strain at time t+dt

EPSI_t(6) -inelastic strain at time t
EPSI_tdt(6)-inelastic strain at time t+dt
PEPSI_tdt(6)-inelastic strain at time t+dt stored from the last iteration

EPSID_t(6)-inelastic strain rate at time t
EPSID_tdt(6)-inelastic strain rate at time t+dt
PEPSID(6)-inelastic strain rate at time t+dt stored from the last iteration

EFIEPSD-effective inelastic strain rate at time t+dt

10.STATE VARIABLES:

```
Z_t -drag stress at time t
Z_tdt -drag stress at time t+dt

OM_t(6) -total back stress at time t
OM_tdt(6) -total back stress at time t+dt
POM(6) -total back stress at time t+dt from the previous
                iteration

OMI_t(6) -inelastic back stress at time t
OMI_tdt(6)-inelastic back stress at time t+dt
POMI(6) -inelastic beck stress rate at time t+dt from the
                previous iteration

OMID_t(6)-inelastic back stress rate at time t
OMID_tdt(6)-inelastic back stress rate at time t+dt
POMID(6) -inelastic back stress rate at time t+dt from
                the previous iteration

AK2 - K2 value at time t+dt
```

11.TIME VARIABLES:

```
TIME -time for the present time step (same as t+dt)
dt   -time increment (=TIME-previous time)
TPRINT-time at which output was printed last
```

12.WORK VARIABLES:

```
WRK_t -total inelastic work at time t
WRK_tdt -total inelastic work at time t+dt
DELWRK -increment of work from time t to time t+dt
```

13.TEMPERATURE VARIABLES:

```
TEMP       -temperature at time t+dt
TEM1,TEM2 -two input temperatures between which TEMP
           lies (used for interpolation of matl const.)
```

14.OTHER VARIABLES:

```
ITER -number of iterations
NCODE-convergence code
      =0 converged
      =1 not converged
IERCOD-code passed on to error printing subroutine
```

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PRIVACY MARKING:

1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-005-619	ARL-STRUC-TM-513	MAY 1989	AIR 86/012

4. TITLE
A SUMMARY OF THE BODNER-STOUFFER CONSTITUTIVE MODEL (U)

5. SECURITY CLASSIFICATION (PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF.(C) RESTRICTED (R), UNCLASSIFIED (U)).

DOCUMENT	TITLE	ABSTRACT
U	U	U

6. NO. PAGES: 15

7. NO. REFS.: 4

8. AUTHOR(S)
N. BRIDGFORD

9. DOWNGRADING/DELIMITING INSTRUCTIONS
Not applicable.

10. CORPORATE AUTHOR AND ADDRESS

AERONAUTICAL RESEARCH LABORATORY
P.O. BOX 4331, MELBOURNE VIC 3001

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Creep properties
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15. DRDA SUBJECT CATEGORIES
0046E
0071L

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16. ABSTRACT (CONT.)

17. IMPRINT

AERONAUTICAL RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. COST CODE	20. TYPE OF REPORT AND PERIOD COVERED
Aircraft Structures Technical Memorandum 513	211080	

21. COMPUTER PROGRAMS USED

Model 2 FORTRAN program

22. ESTABLISHMENT FILE REF.(S)

23. ADDITIONAL INFORMATION (AS REQUIRED)